Lesson 2

Heat Balance of the Atmosphere

This lesson and the two that follow introduce the fundamental concepts of meteorology—the science of the atmosphere and its phenomena. In Lesson 1, you learned that meteorology plays an important role in understanding air pollutant transport and dispersion. Lessons 2 and 3 cover basic meteorological principles that produce atmospheric motion. Lesson 4 builds on basic meteorological concepts and principles in its discussion of the atmosphere's vertical temperature structure and air pollution dispersion.

Goal

To familiarize you with the source of energy responsible for atmospheric motion, and with the way the earth and atmosphere combine to balance the energy received by the earth-atmosphere system.

Objectives

Upon completing this lesson, you will be able to do the following:

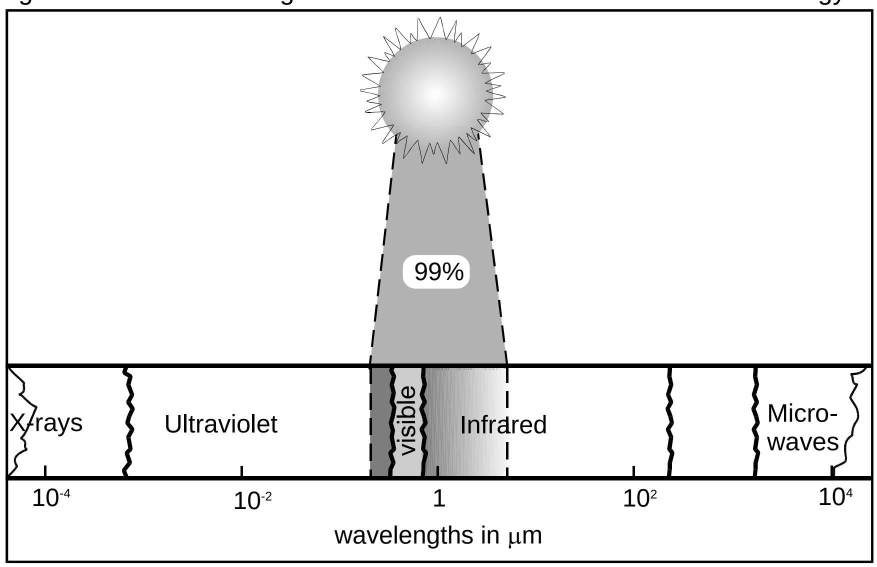
1. Identify the source of energy that "drives" atmospheric motion.
2. Define insolation and describe four factors that govern the amount of insolation received by the earth-atmosphere.
3. Explain the greenhouse effect and name the most important heat storage constituent of the atmosphere.
4. Explain the reason for a long-term heat balance in the atmosphere.
5. Describe three heat transfer methods: conduction, convection, and advection.
6. Define differential heating and identify at least three factors that influence it.

Radiation and Insolation

The energy expended in virtually all atmospheric processes is originally derived from the sun. This energy is transferred by radiation of heat in the form of electromagnetic waves. The radiation from the sun has its peak energy transmission in the visible wavelength range [0.38 to 0.78 micrometers (μm)] of the electromagnetic spectrum (Figure 2-1). However, the sun also releases considerable energy in the ultraviolet and infrared regions. Ninety-nine percent of the sun's energy is emitted in wavelengths between 0.15 to 40 μm.

Furthermore, wavelengths longer than 2.5 μm are strongly absorbed by water vapor and carbon dioxide in the atmosphere. Radiation at wavelengths less than 0.29 μm is absorbed high in the atmosphere by nitrogen and oxygen. Therefore, solar radiation striking the earth generally has a wavelength between 0.29 and 2.5 μm.

Figure 2-1. Wavelengths at which the sun radiates 99% of its energy



Source for data: Moran and Morgan 1994.

The amount of <u>in</u>coming <u>sol</u>ar radi<u>ation</u> received at a particular time and location in the earth-atmosphere system is called *insolation*. Insolation is governed by four factors:

- Solar constant
- Transparency of the atmosphere
- Daily sunlight duration
- Angle at which the sun's rays strike the earth

Solar Constant

The **solar constant** is the average amount of radiation received at a point, perpendicular to the sun's rays, that is located outside the earth's atmosphere at the earth's mean distance from the sun. The actual amount of solar radiation received at the outer edge of the atmosphere would vary slightly depending on the energy output of the sun and the distance of the earth relative to the sun. Due to the eccentricity of the earth's orbit around the sun, the earth is closer to the sun in January than in July. Also, the radiation emitted from the sun varies slightly, probably less than a few percent. These slight variations that affect the solar constant are trivial considering the atmospheric properties that deplete the overall amount of solar radiation reaching the earth's surface. Transparency of the atmosphere, duration of daylight, and the angle at which the sun's rays strike the earth are much more important in influencing the amount of insolation actually received, which in turn influences the weather.

Table 2-1. Values for solar constant	
Solar constant =	1.94 cal/cm^2 min
	1,353 W/m^2
	428 Btu/ft^2 hr
	4,871 kJ/m^2 hr

Transparency

Transparency of the atmosphere does have an important bearing upon the amount of insolation that reaches the earth's surface. The emitted radiation is depleted as its passes through the atmosphere. Different atmospheric constituents absorb or reflect energy in different ways and in varying amounts. Transparency of the atmosphere refers to how much radiation penetrates the atmosphere and reaches the earth's surface without being depleted. As shown in Figure 2-2, some of the radiation received by the atmosphere is reflected from the tops of clouds and from the earth's surface and some is absorbed by molecules and clouds.

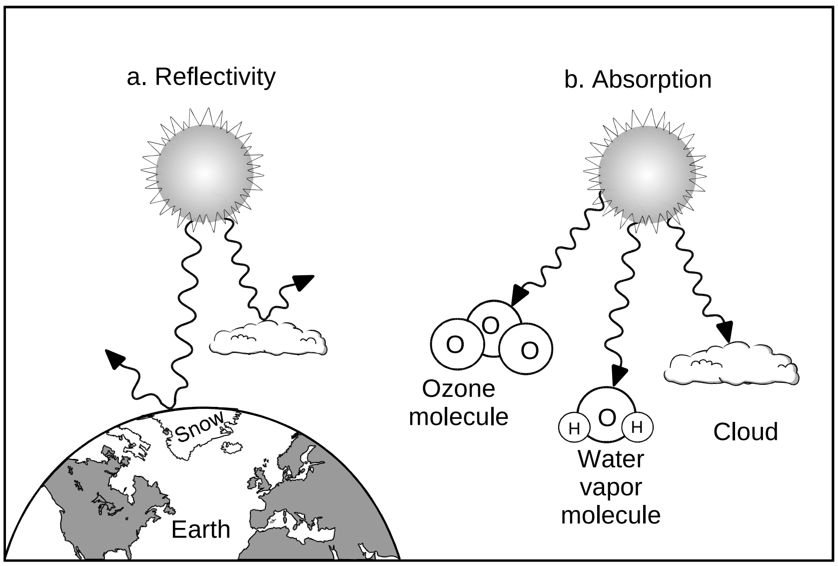


Figure 2-2. Two factors that reduce atmospheric transparency

The general reflectivity of the various surfaces of the earth is referred to as the albedo. **Albedo** is defined as the fraction (or percentage) of incoming solar energy that is reflected back to space. Different surfaces (water, snow, sand, etc.) have different albedo values (Table 2-2). For the earth and atmosphere as a whole, the average albedo is 30% for average conditions of cloudiness over the earth. This reflectivity is greatest in the visible range of wavelengths.

Table 2-2. Albedo values for various surfaces	
Surface	**Albedo (as a percentage of incoming short-wave radiation)**
Black soil, dry	14
Black soil, moist	8
Plowed field, moist	14
Sand, bright, fine	37
Dense, dry and clean snow	86-95
Sea ice, slightly porous milky bluish	36
Ice sheet, covered by a water layer of 15-20 cm	26
Woody farm covered with snow	33-40
Deciduous forest	17
Tops of oak	18
Pine forest	14
Desert shrub land	20-29
Swamp	10-14
Prairie	12-13
Winter wheat	16-23
Heather	10
Yuma, Arizona	20
Washington, D.C. (September)	12-13
Winnipeg, Manitoba (July)	13-16
Great Salt Lake, Utah	3

Source: Drake, R.L. et al. 1979.

Some of the gases in the atmosphere (notably water vapor) absorb solar radiation, causing less radiation to reach the earth's surface. Water vapor, although comprising only about 3% of the atmosphere, on the average absorbs about six times as much solar radiation as all other gases combined. The amount of radiation received at the earth's surface is therefore considerably less than that received outside the atmosphere as represented by the solar constant.

All bodies, not just the sun, radiate energy at wavelengths somewhere along the electromagnetic spectrum. Warmer bodies radiate shorter wavelengths, while cooler bodies radiate longer wavelengths. Whereas the sun has its peak transmission in the visible range (0.38 to 0.78 μm), the earth emits its maximum radiation at considerably longer wavelengths—in the 10 μm range (infrared region). The earth warms up when it *absorbs* energy and cools when it *radiates* energy. The earth absorbs and emits radiation at the same time. If the earth's surface absorbs more energy than it radiates, it will heat up. If the earth's surface radiates more energy than it absorbs, it will cool.

The earth absorbs short-wave solar radiation and emits longer wavelength **terrestrial radiation.** In the atmosphere, clouds, water vapor, and to a lesser extent carbon dioxide absorb terrestrial radiation, which causes the atmosphere to warm. The atmosphere absorbs much more terrestrial radiation than solar radiation. The atmosphere also radiates energy to outer space and back to the earth's surface. The earth-atmosphere system emits terrestrial radiation continuously, both day and night. The atmospheric absorption of terrestrial radiation benefits the earth-atmosphere by absorbing radiation that would otherwise be lost to space. This phenomenon explains the reason air temperatures are **usually** warmer on nights with cloud cover than on clear nights. The **greenhouse effect** is the descriptive name given to the result of the energy exchange process that causes the earth's surface to be warmer than it would be if the atmosphere did not radiate energy back to the earth.

Gases such as carbon dioxide and methane also increase the ability of the atmosphere to absorb radiation. Some scientists believe that increased manmade emissions of these naturally occurring compounds (and other similarly behaving gases often called **greenhouse gases**) are heating up the earth and atmosphere more rapidly than would occur naturally. This phenomenon is often referred to as **global warming**. Table 2-3 lists the predominant greenhouse gases. Furthermore, some scientists predict that gradual changes in climatic conditions could occur if this purported warming trend continues. Currently, studies are being conducted to determine if manmade emissions are significantly contributing to global warming.

Table 2-3. The greenhouse gases

Greenhouse gas	% of total greenhouse gases	Sources and % of total greenhouse gases
Carbon dioxide (CO_2)	50	Energy from fossil fuels (35) Deforestation (10) Agriculture (3) Industry (2)
Methane (CH_4)	16	Energy from fossil fuels (4) Deforestation (4) Agriculture (8)
Nitrous oxide (N_2O)	6	Energy from fossil fuels (4) Agriculture (2)
Chlorofluorocarbons (CFCs)	20	Industry (20)
Ozone (O_3)	8	Energy from fossil fuels (6) Industry (2)

Source: Williams, M. 1993.

Transparency is a function not only of cloudiness, but also of latitude. The sun's rays must pass through a thicker layer of reflecting-scattering atmosphere at middle and high latitudes than at tropical latitudes (Figure 2-3). This effect varies with the seasons, being greatest in winter (in the northern hemisphere) when the earth's axis is tilted away from the sun causing the sun's rays to be low on the horizon (Figure 2-4).

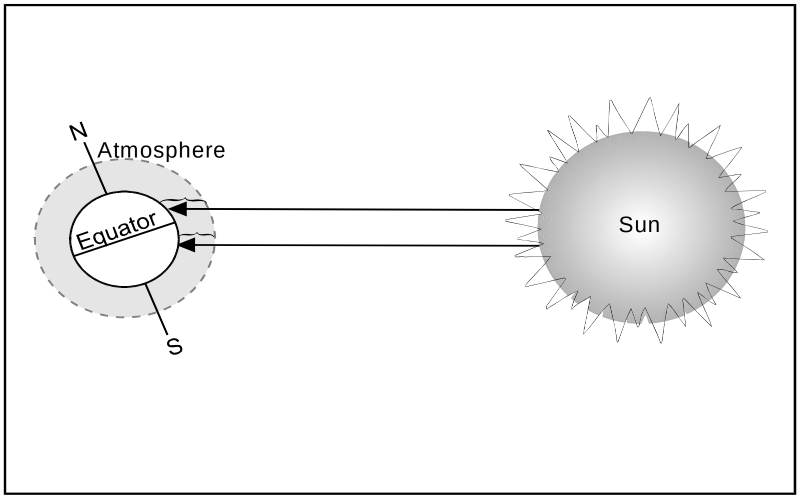
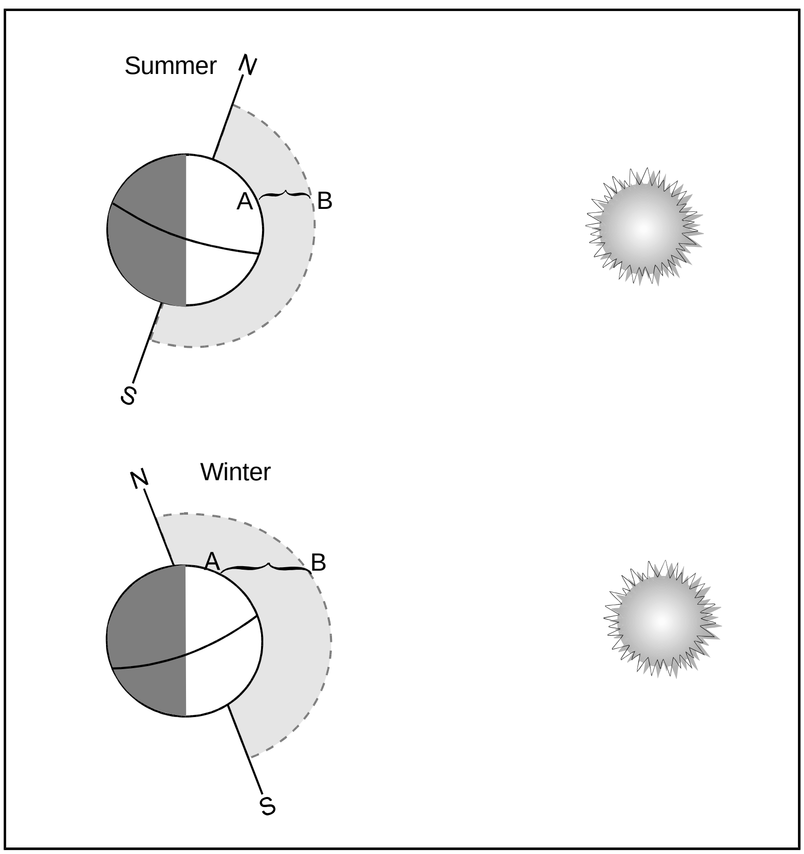


Figure 2-3. Relationship of transparency to latitude

Figure 2-4. Seasonal effect of transparency at a particular location



Daylight Duration

The duration of daylight also affects the amount of insolation received: the longer the period of sunlight, the greater the total possible insolation. Daylight duration varies with latitude and the seasons. At the equator, day and night are always equal. In the polar regions, the daylight period reaches a maximum of twenty-four hours in summer and a minimum of zero hours in winter. Figure 2-5 shows how the amount of daylight changes with the seasons at a particular location.

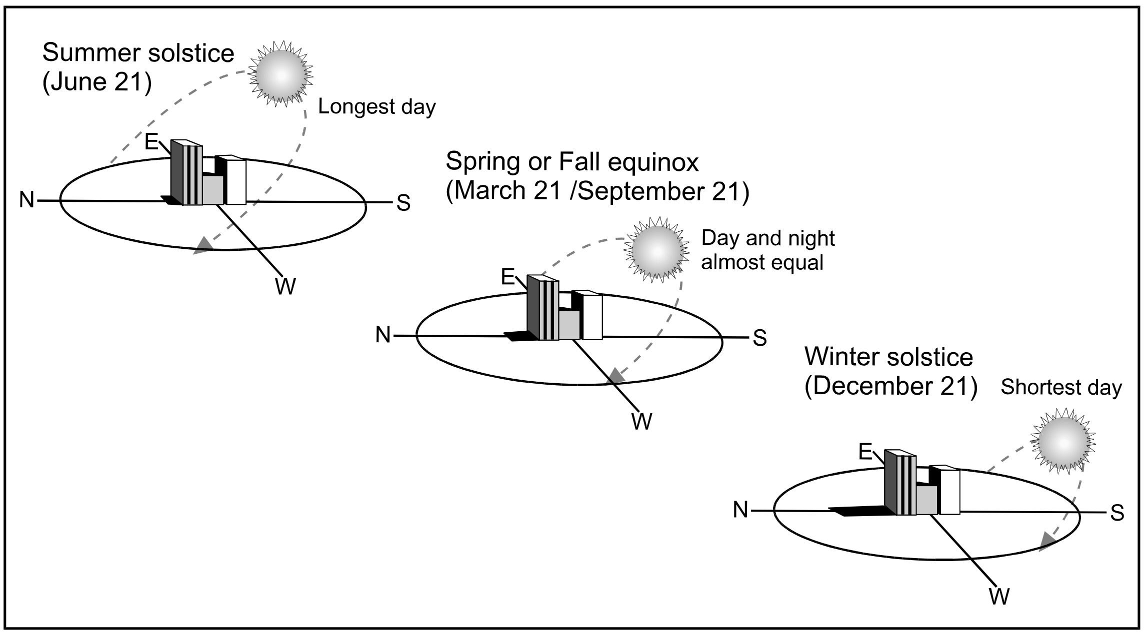


Figure 2-5. Seasonal variations in daylight duration

Angle of Rays

The angle at which the sun's rays strike the earth varies considerably as the sun "shifts" back and forth across the equator. A relatively flat surface perpendicular to an incoming vertical sun ray receives the largest amount of insolation. Therefore, areas at which the sun's rays are oblique receive less insolation because the oblique rays must pass through a thicker layer of reflecting and absorbing atmosphere and are spread over a greater surface area (Figure 2-6). This same principle also applies to the daily shift of the sun's rays. At solar noon, the intensity of insolation is greatest. In the morning and evening hours, when the sun is at a low angle, the amount of insolation is small.

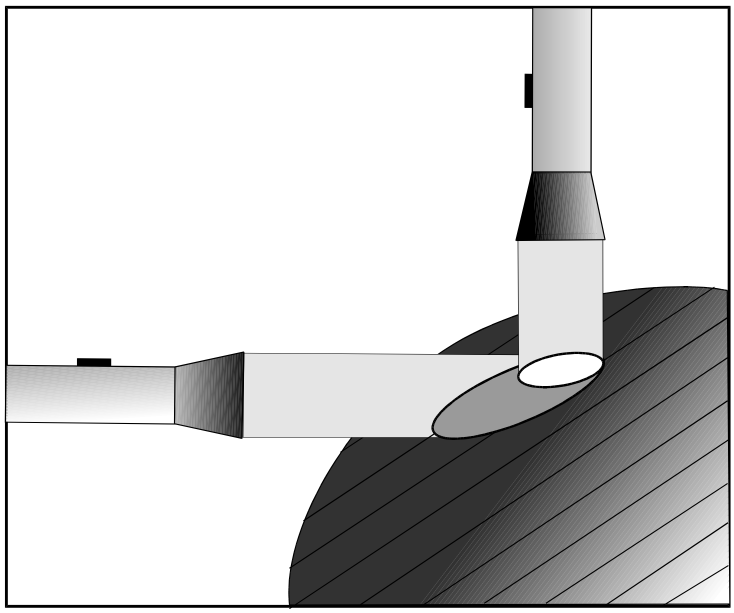


Figure 2-6. Oblique and vertical rays

Heat Balance

Since energy from the sun is always entering the atmosphere, the earth would overheat if all this energy were stored in the earth-atmosphere system. So, energy must eventually be released back into space. On the whole, this is what happens. Incoming radiation eventually goes back out as terrestrial radiation, and a heat balance, called the **radiational balance** results.

Figure 2-7 depicts the radiation (heat) balance of the atmosphere. For every 100 units of energy that enters the atmosphere, 51 units are absorbed by the earth, 19 units are absorbed in the atmosphere and 30 units are reflected back to space. The 70 units that are absorbed by the earth-atmosphere system (51 units +19 units) are eventually reradiated to space as long wave radiation.

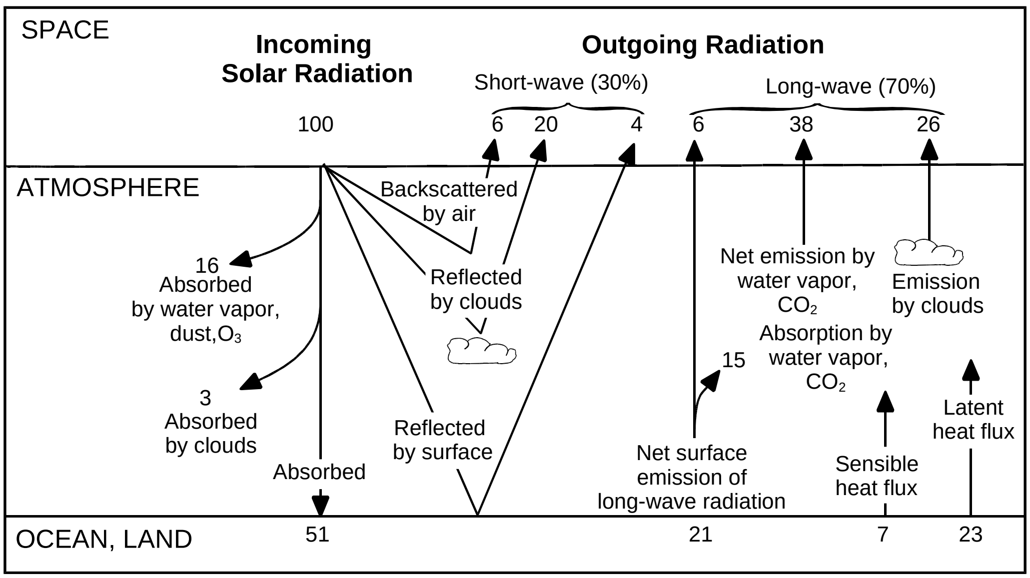


Figure 2-7. The mean annual radiation and heat balance of the atmosphere relative to 100 units of incoming solar radiation
Source: National Academy of Sciences 1975, p. 18.

Heat Distribution

The earth, as a whole, experiences great contrasts in heat and cold at any particular time. Warm, tropical breezes blow at the equator while ice caps are forming in the polar regions. In fact, due to the extreme temperature differences at the equator and the poles, the earth-atmosphere system resembles a giant "heat engine." Heat engines depend on hot-cold contrasts to generate power. As you will see, this global "heat engine" influences the major atmospheric circulation patterns as warm air is transferred to cooler areas. Different parts of the earth receiving different amounts of insolation account for much of this heat imbalance. As discussed earlier, latitude, the seasons, and daylight duration cause different locations to receive varying amounts of insolation.

Differential Heating

Not only do different amounts of solar radiation reach the earth's surface, but different earth surfaces absorb heat energy at different rates. For example, land masses absorb and store heat differently than water masses. Also, different types of land surfaces vary in their ability to absorb and store heat. The color, shape, surface texture, vegetation and presence of buildings can all influence the heating and cooling of the ground. Generally, dry surfaces heat and cool faster than moist surfaces. Plowed fields, sandy beaches, and paved roads become hotter than surrounding meadows and wooded areas. During the day, the air over a plowed field is warmer than over a forest or swamp; during the night, the situation is reversed. The property of different surfaces which causes them to heat and cool at different rates is referred to as **differential heating**.

Absorption of heat energy from the sun is confined to a shallow layer of land surface. Consequently, land surfaces heat rapidly during the day and cool quickly at night. Water surfaces, on the other hand, heat and cool more slowly than land surfaces for the following reasons:

- Water movement distributes heat
- The sun's rays are able to penetrate the water surface
- More heat is required to change the temperature of water due to its higher specific heat. (It takes more energy to raise the temperature of water than it does to change the temperature of the same amount of soil.)
- Evaporation of water occurs which is a cooling process

Transport of Heat

In addition to radiation, heat is transferred by conduction, convection, and advection. These processes affect the temperature of the atmosphere near the surface of the earth. **Conduction** is the process by which heat is transferred through matter without the transfer of matter itself. For example, the handle of an iron skillet becomes hot due to the conduction of heat from the stove burner. Heat is conducted from a warmer object to a cooler one. Heat transfer by **convection** occurs when matter is in motion. Air that is warmed by a heated land surface (by conduction) will rise because it is lighter than the surrounding air. This heated air rises, transferring heat vertically. Likewise, cooler air aloft will sink because it is heavier than the surrounding air. This goes hand in hand with rising air and is part of heat transfer by convection. Meteorologists also use the term **advection** to denote heat transfer that occurs mainly by horizontal motion rather than by vertical movement of air (convection).

Global Distribution of Heat

As mentioned before, the world distribution of insolation is closely related to latitude. Total annual insolation is greatest at the equator and decreases toward the poles. Figure 2-8 shows the amount of solar radiation absorbed by the earth and atmosphere (dotted line) compared to the long wave radiation leaving the atmosphere (solid line). The amount of insolation received annually at the equator is over four times that received at either of the poles. As the rays of the sun shift seasonally from one hemisphere to the other, the zone of maximum possible daily insolation moves with them. For the earth as a whole, the gains in solar energy equal the losses of energy back into space (heat balance). However, since the equatorial region does gain more heat than it loses and the poles lose more heat than they gain (as shown in Figure 2-8), something must happen to distribute heat more evenly around the earth. Otherwise, the equatorial regions would continue to heat and the poles would continue to cool. Therefore, in order to reach equilibrium, a continuous large-scale transfer of heat (from low to high latitudes) is carried out by atmospheric and oceanic circulations.

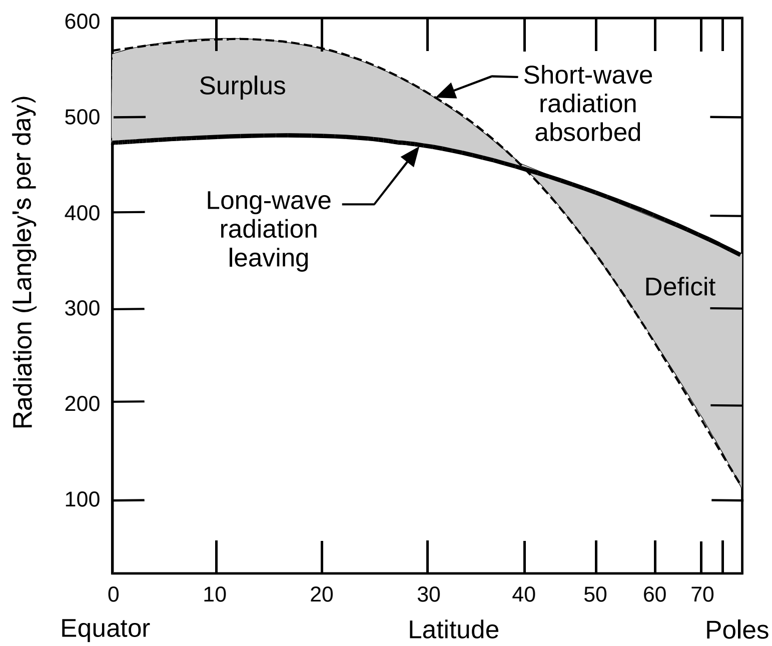


Figure 2-8. Latitudinal distribution of heat

The atmosphere drives warm air poleward and brings cold air toward the equator. Heat transfer from the tropics poleward takes place throughout the year, but at a much slower rate in summer than in winter. The temperature difference between low and high latitudes is considerably smaller in summer than in winter (only about half as large in the Northern Hemisphere). As would be expected, the winter hemisphere has a net energy loss and the summer hemisphere a net gain. Most of the summertime gain is stored in the surface layers of land and ocean, mainly in the ocean.

The oceans also play a role in heat exchange. Warm water flows poleward along the western side of an ocean basin and cold water flows toward the equator on the eastern side. At higher latitudes, warm water moves poleward in the eastern side of the ocean basin and cold water flows toward the equator on the western side. The oceanic currents are responsible for about 40 percent of the transport of energy from the equator to the poles. The remaining 60 percent is attributed to the movement of air.

Review Exercise

1. The source of energy responsible for atmospheric and oceanic motion is the ____________________.

2. List the four factors that govern the amount of insolation received by the earth.

   ____

   ____

   ____

   ____

3. The fraction of energy reflected by a surface compared to the amount incident on the surface is its:

   a. Atmosphere
   b. Albedo
   c. Heat balance
   d. Solar constant

4. Which one of the following substances stores more heat energy than all other atmospheric constituents combined?

   a. Carbon dioxide
   b. Ozone
   c. Water vapor
   d. Nitrogen

5. When the air is cloudy or heavily polluted, ____________________ direct insolation will be received at the earth's surface.

   a. More

   b. Less

   Explain why.

   ____

   ____

6. Explain the greenhouse effect.

   ____

   ____

7. True or False? Oblique rays produce more heating per unit area than vertical rays do.

   a. True
   b. False

8. Since the earth's atmosphere depletes solar radiation passing through it, how much radiation received at the outermost boundary of the atmosphere reaches the surface of the earth?
   a. One-quarter of it
   b. Half of it
   c. All of it
   d. None of it

9. A heat balance on the earth implies that:
   a. The cold earth holds all of the heat it receives
   b. The cold poles hold as much heat as the warm equator radiates
   c. The earth-atmosphere loses as much heat as it gains
   d. The earth warms in the winter and cools in the summer

10. What is differential heating?

    ____

    ____.

11. True or False? Heat transfer by conduction involves the movement of matter.
    a. True
    b. False

12. When air touches the heated earth and in turn becomes warm, ____________________ has just occurred.

13. The heating process that causes the vertical mixing of the air above the earth's surface is called:
    a. Conduction
    b. Convection
    c. Advection

14. True or False? Oceanic and atmospheric circulations redistribute energy received by the sun.
    a. True
    b. False

Review Exercise Answers

1. **Sun**

   The source of energy responsible for atmospheric and oceanic motion is the sun.

2. **Solar constant**
   Atmosphere's transparency
   Daily sunlight duration
   Angle at which the sun's rays strike the earth

   The four factors that govern the amount of insolation received by the earth are:

   - Solar constant
   - Atmosphere's transparency
   - Daily sunlight duration
   - Angle at which the sun's rays strike the earth

3. **b. Albedo**

   The fraction of energy reflected by a surface compared to the amount incident on the surface is its albedo.

4. **c. Water vapor**

   Water vapor stores more heat energy than all other atmospheric constituents combined.

5. **b. Less**

   When the air is cloudy or heavily polluted, less direct insolation will be received because atmospheric gases and clouds absorb and reflect solar radiation.

6. The **greenhouse** effect is the ability of the atmosphere to absorb terrestrial radiation and reradiate heat back to the earth's surface.

7. **b. False**

   Oblique rays produce less heating per unit area than vertical rays do.

8. **b. Half of it**

   The Earth's atmosphere depletes solar radiation passing through it; half of the radiation received at the outermost boundary of the atmosphere reaches the earth’s surface.

9. **c. The earth-atmosphere loses as much heat as it gains**

   A heat balance on the earth implies that the earth-atmosphere loses as much heat as it gains.

10. **Differential heating** is the ability of some objects to absorb and hold heat better than others.

11. **b. False**

Heat transfer by conduction does not involve the movement of matter. Conduction is the process by which heat is transferred through matter without the transfer of matter itself.

12. **Conduction**

    When air touches the heated earth and in turn becomes warm, conduction has just occurred.

13. **b. Convection**

    The heating process that causes the vertical mixing of the air above the earth's surface is called convection.

14. **a. True**

    Oceanic and atmospheric circulations redistribute energy received by the sun.